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Richard W. Healy
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Groundwater recharge

1.1 Introduction

Groundwater is a critical source of fresh water throughout the world. Comprehensive statistics on groundwater abstraction and use are not available, but it is estimated that more than 1.5 billion people worldwide rely on groundwater for potable water (Clarke *et al.*, 1996). Other than water stored in icecaps and glaciers, groundwater accounts for approximately 97% of fresh water on Earth (Nace, 1967; Shiklomanov and Rodda, 2003). As the world population continues to grow, more people will come to rely on groundwater sources, particularly in arid and semiarid areas (Simmers, 1990). Long-term availability of groundwater supplies for burgeoning populations can be ensured only if effective management schemes are developed and put into practice. Quantification of natural rates of groundwater recharge (i.e. the rates at which aquifer waters are replenished) is imperative for efficient groundwater management (Simmers, 1990). Although it is one of the most important components in groundwater studies, recharge is also one of the least understood, largely because recharge rates vary widely in space and time, and rates are difficult to directly measure.

The rate, timing, and location of recharge are important issues in areas of groundwater contamination as well as groundwater supply. In general, the likelihood for contaminant movement to the water table increases as the rate of recharge increases. Areas of high recharge are often equated with areas of high aquifer vulnerability to contamination (ASTM, 2008; US National Research Council, 1993). Locations for subsurface waste-disposal facilities often are selected on the basis of relative rates of recharge, with ideal locations being those with low aquifer vulnerability so as to minimize the amount of moving water coming into contact with waste (e.g. US Nuclear Regulatory Commission, 1993). A high profile example of the importance of susceptibility to contamination is the study for the proposed high-level radioactive-waste repository at Yucca Mountain, Nevada. Tens of millions of dollars were invested over the course of two decades in efforts to determine recharge rates at the site (Flint *et al.*, 2001a).

Computer models of groundwater-flow are perhaps the most useful tools available for groundwater-resource management. Models are applied in both water-supply and aquifer-vulnerability studies. We expect that many readers of this book will be modelers seeking recharge estimates for use in groundwater-flow models or for evaluating model results.

The primary objective of this text is to provide a critical evaluation of the theory and assumptions that underlie methods for estimating rates of groundwater recharge. A complete understanding of theory and assumptions is fundamental to proper application of any method. Good practice dictates that recharge estimation techniques be matched to conceptual models of

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recharge processes at individual sites to ensure that assumptions underlying the techniques are consistent with conceptual models. As such, the text should serve as a resource to which hydrologists can refer for making informed decisions on the selection and application of methods. A thorough understanding of methods also provides a framework for the analysis of implications of modifying methods or applying them under less-than-ideal conditions.

A conceptual model of recharge processes attempts to answer the questions of where, when, and why recharge occurs. The model will thus identify the prominent recharge mechanisms, perhaps provide initial estimates of recharge rates, and serve as a guide for the selection of methods and for deciding on locations and time frames for data collection. The importance of matching methods for estimating recharge with conceptual models cannot be overemphasized. Development of a sound conceptual model is imperative for selecting proper methods and obtaining meaningful recharge estimates, but this process can be difficult, complicated by both natural and anthropogenic factors. A conceptual model often evolves over time as data are collected and interpreted; there may be a dynamic feedback effect – recharge estimates may support revision of the conceptual model or suggest the application of alternative methods.

Nature is complex, and each study site is unique. Although conceptual models of recharge processes are important, the development of a conceptual model is not the main focus of this book. Because of the great complexity and limitless variability in hydrologic systems, it is beyond the scope of this text to provide more than general guidelines for developing a conceptual model of recharge processes. It is simply not practical to describe or examine every scenario under which a method will be applied. Section 1.4 provides a general review of critical components of a conceptual model. For illustrative purposes, typical recharge processes in groundwater regions of the United States are briefly discussed in the final chapter.

This text is not intended as a cookbook that provides a recipe for estimating recharge for any and all situations; application of any method requires some hydrologic analysis. However, many of the methods described are simple enough that all the details required for their application are contained herein. Other methods, such as the use of complex models, require training that is beyond the scope of this text. Information is provided on these methods to assist the reader in deciding whether the cost of such training will be balanced by the benefits gained from applying the methods. Applications are illustrated with examples to highlight benefits and limitations. Many references are provided to allow the interested reader to pursue more details on any of the methods discussed.

Most of the discussion in this text is directed toward quantifying rates of natural recharge; however, many methods can and have been used to estimate recharge from artificial recharge operations, irrigated areas, and human-made drainage features, such as canals and urban water-delivery systems. In addition, many of the methods can be used to provide qualitative information on recharge rates (i.e. identifying areas of high and low relative recharge rates) for purposes of determining aquifer vulnerability to contamination from surface sources.

Numerous journal articles and reports describe the theory and details of the various techniques for estimating recharge. Applications of methods are discussed in many other papers. Given the importance of the subject matter, the paucity of textbooks devoted to this topic is surprising. Lerner *et al.* (1990) is the most thorough of these publications in terms of method descriptions. That text provides generic descriptions of physical controls that influence recharge in different hydrogeological provinces and discussion of techniques based on source of recharge water (i.e. precipitation, rivers, irrigation, and urbanization). Wilson (1980), Simmers (1997), and Kinzelbach *et al.* (2002) provide informative discussions on recharge processes in arid and semiarid regions and the techniques that are applicable in those regions. Simmers (1988) is a compendium of papers associated with a conference devoted to groundwater recharge. Hogan *et al.* (2004) and Stonestrom *et al.* (2007) each comprise a series

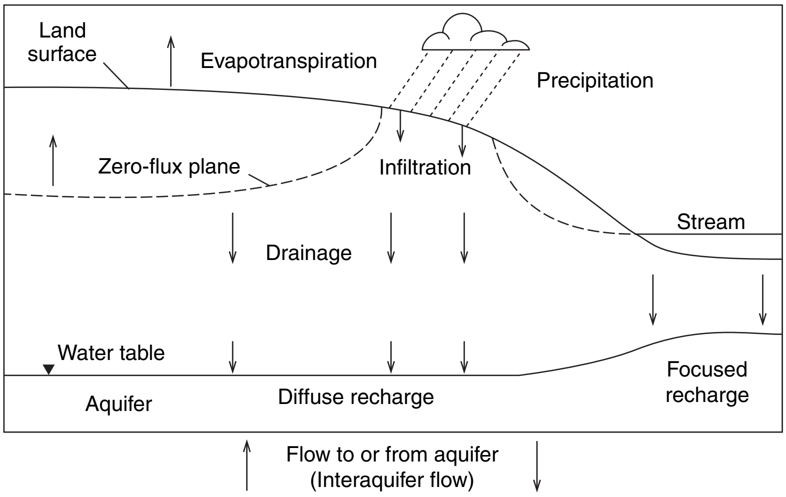

Figure 1.1 Vertical cross section showing infiltration at land surface, drainage through the unsaturated zone, diffuse and focused recharge to an unconfined aquifer, flow between the unconfined aquifer and an underlying confined aquifer (interaquifer flow), and the zero-flux plane.

of papers on recharge processes and case studies of recharge in arid and semiarid regions of the southwestern United States.

1.2 Terminology

Recharge is defined, herein, as the downward flow of water reaching the water table, adding to groundwater storage. This definition is similar to those given by Meinzer (1923), Freeze and Cherry (1979), and Lerner *et al.* (1990). Strictly speaking, this definition does not include water flow to an aquifer from an adjoining groundwater system (such as water movement from an unconfined aquifer across a confining bed to an underlying aquifer); we refer to this flow as *interaquifer flow*. Others include this flow in their definition of recharge. Interaquifer flow has also been referred to as groundwater underflow. Regardless of terminology, methods for estimating interaquifer flow are included in this text. Recharge is usually expressed as a volumetric flow, in terms of volume per unit time (L^3/T), such as m^3/d, or as a flux, in terms of volume per unit surface area per unit time (L/T), such as mm/yr.

Recharge occurs through diffuse and focused mechanisms (Figure 1.1). *Diffuse* recharge is recharge that is distributed over large areas in response to precipitation infiltrating the soil surface and percolating through the unsaturated zone to the water table; diffuse recharge is sometimes referred to as *local* recharge (Allison, 1987) or *direct* recharge (Simmers, 1997). *Focused* recharge is the movement of water from surface-water bodies, such as streams, canals, or lakes, to an underlying aquifer. Focused recharge generally varies more in space than diffuse recharge. A distinction between different types of focused recharge has been proposed by Lerner *et al.* (1990), with *localized* recharge defined as concentrated recharge from small depressions, joints, or cracks, and *indirect* recharge defined as recharge from mappable features such as rivers, canals, and lakes. Groundwater systems receive both diffuse and focused recharge, but the importance of each mechanism varies from region to region and even from site to site within a region. Generally, diffuse recharge dominates in humid settings; as the degree of aridity increases, the importance of focused recharge in terms of total aquifer replenishment also tends to increase (Lerner *et al.*, 1990). Some methods addressed in this book are designed to estimate diffuse recharge; others are specific to focused recharge.

Infiltration is the entry of water into the subsurface. Infiltrating water can be viewed as *potential recharge*; it may become recharge, but it may instead be returned to the atmosphere by evapotranspiration, or it may simply remain in storage in the unsaturated zone for some period of time. The *zero-flux plane* (ZFP) is the horizontal

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plane at some depth within the unsaturated zone that separates upward and downward moving water; the ZFP is sometimes equated with the bottom of the root zone (Figure 1.1). Water above the ZFP moves upward in response to evapotranspiration demand; water beneath the ZFP drains downward, eventually arriving at the water table. The depth of the ZFP changes in response to infiltration and evapotranspiration, ranging from land surface (for the case of downward water movement throughout the unsaturated zone) to some depth beneath the water table (for the case of groundwater evapotranspiration). Water draining beneath the ZFP in the unsaturated zone is referred to as *drainage*, *percolation*, or *net infiltration*; it becomes actual recharge when it arrives at the water table. Some techniques described in this book provide estimates of potential recharge; others provide estimates of drainage; and some methods provide estimates of actual recharge.

For clarity, we use the term *groundwater* to refer to water beneath the water table (within the saturated zone) and the term *pore water* to refer to water above the water table (within the unsaturated zone). A *point* estimate pertains to recharge at a specific point in space or time, whereas an *integrated* estimate refers to a value of recharge that is averaged over some larger space or time scale.

Different climatic regions are referred to throughout the text. Climatic regions are classified on the basis of annual precipitation. An *arid* climate is one with annual precipitation of less than 250 mm; a *semiarid* region has precipitation rates between 250 and 500 mm/yr; a *subhumid* climate refers to precipitation rates between 500 and 1000 mm/yr; and *humid* climates have annual precipitation rates that exceed 1000 mm.

1.3 Overview of the text

This text is organized by methods, which are grouped on the basis of types of required or available data (e.g. methods based on water budgets, or on data obtained from the unsaturated zone, or on streamflow data). Our approach differs from that of Lerner *et al.* (1990) and Wilson (1980), who chose to organize methods on the basis of source of recharge (precipitation, rivers, etc.). While there is perhaps no ideal format for this presentation, the format used in this text has proved workable within the classroom over the decade and a half that we have taught this material. Examples are given to show how methods can be applied for different sources of recharge water.

This first chapter provides an introduction to the book, emphasizing the importance of developing a conceptual model of recharge processes for the area of interest. Chapters 2 through 8 are the heart of the book. They provide in-depth analysis of methods for estimating recharge. The format for each presentation is similar: discussion of theory and assumptions, advantages and limitations of the methods, and description of example case studies. Each chapter is devoted to a particular family of methods. Water-budget methods (Chapter 2) are presented first to emphasize the importance of water budgets in all studies.

Water-budget methods are widely used; indeed, most methods for estimating recharge could be classified as water-budget methods. To avoid making Chapter 2 too long, its content is limited to the use of the residual water-budget method, whereby a water-budget equation is derived for a control volume, such as a watershed or an aquifer. All components within that equation, except for recharge, are measured or estimated; recharge is then set equal to the residual in the equation. Other methods that can be categorized as water-budget methods (e.g. the water-table fluctuation method, the zero-flux plane method, and modeling methods) are described in other chapters. Remote-sensing tools are described in Chapter 2, although they may be useful in other methods as well.

Discussion in Chapter 3 is devoted to the use of models for estimating recharge. A general approach to modeling, applicable to all models, is presented first; a brief description of inverse techniques is included. Unsaturated zone water-budget models, watershed models, groundwater flow models, and integrated surface- and subsurface-flow models are then discussed. Because of the complexities of some models, detailed model descriptions are avoided. Instead, examples are used to highlight capabilities of complex models, resources required for model application, and benefits and limitations of using models to generate estimates of recharge. Empirical equations, which are widely used for predicting recharge, are also described, as are regression and geostatistical techniques for upscaling point estimates of recharge to obtain average values for an aquifer or watershed.

Chapter 4 addresses physical methods that are based on surface-water data. Included are stream water-budget methods, seepage meters, streamflow-duration curves, streamflow hydrograph analysis (hydrograph separation), and chemical or isotopic hydrograph separation.

Chapter 5 describes physical methods that can be applied on the basis of data collected in the unsaturated zone. These methods include the zero-flux plane, the Darcy method, and the use of lysimeters. Physical methods based on data collected in the saturated zone form the basis of Chapter 6. The primary method in this group is the water-table fluctuation method. The Darcy method and methods based on time series of measured groundwater levels are also discussed.

Chapters 7 and 8 are devoted to the use of tracers for estimating recharge. Chemical and isotopic tracer methods are described in Chapter 7. Tracers can be naturally occurring (e.g. chloride and isotopes of carbon and hydrogen), can occur as an indirect outcome of anthropogenic activity (e.g. tritium, chlorine-36, and chlorofluorocarbon gases), or can be intentionally applied to the surface or subsurface for experimental purposes (e.g. bromide, fluorescent dyes). Tracers can be used to study water from any source. Use of heat as a tracer for estimating recharge is described in Chapter 8.

The final chapter, Chapter 9, attempts to link conceptual models of recharge processes with estimation methods. It begins with a discussion of considerations important in selecting methods. Figures and tables are presented to compare methods in terms of spatial and temporal scales of applicability. Typical recharge processes and methods that have been used to study these processes are described for groundwater regions of the United States. This discussion is not an attempt at a comprehensive summary of recharge processes and studies; such an attempt is neither practical nor feasible. Rather, the idea is to illustrate how conceptual models of recharge processes can be formed and used to select appropriate methods. The closing section presents some final thoughts on good practices for any recharge study.

1.4 Developing a conceptual model of recharge processes

The development of a conceptual model of recharge processes (Figure 1.2) is an important step in any recharge study. The conceptual model should be developed at the beginning of a study; it can be revised and adjusted as additional data and analyses provide new insights to the hydrologic system (Zheng and Bennett, 2002; Bredehoeft, 2005). Although this book is focused on methods, the reader should bear in mind the importance of a conceptual model when reviewing various methods. This section provides some discussion on factors that can influence a conceptual model – climate, geology, topography, hydrology, vegetation, and land use. The contents of this section are by no means comprehensive; the intent is to illustrate some of the factors that can help to shape a conceptual model.

Water budgets are fundamental components of any conceptual model of a hydrologic system, providing a link between recharge processes and other processes in the hydrologic cycle. Water-budget equations can be derived for one or more control volumes, such as an aquifer, a watershed, a stream, or even a column of soil (Healy *et al.*, 2007). A water-budget equation allows consideration of the entire hydrology of the system under study, providing information not only on recharge, but also on interrelationships among recharge, discharge, and change in storage. Preliminary water budgets can be readily constructed with existing data and refined as various measurements and

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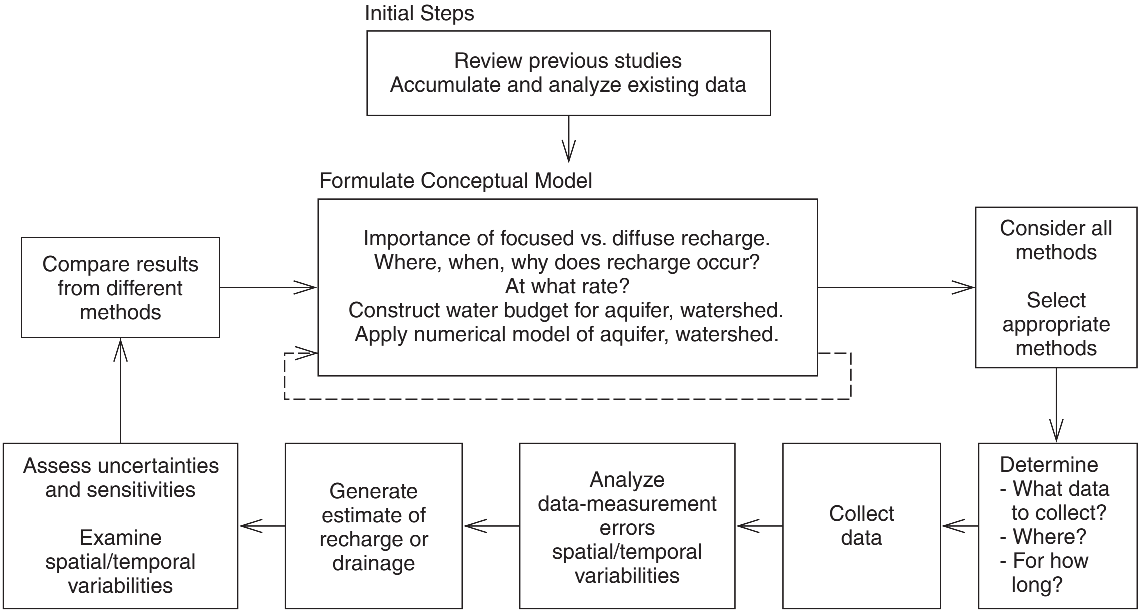

Figure 1.2 Schematic showing iterative process for developing a conceptual model of recharge processes.

recharge estimates are obtained. As noted by Lerner *et al.* (1990), a good method for estimating recharge provides not only an estimate of how much water becomes recharge, but also explains the fate of the remaining water that does not become recharge. Water-budget analyses serve that purpose. In addition, a water-budget equation provides a convenient context for the analysis of assumptions inherent in various estimation techniques.

Although recharge is important in water-supply studies, recharge rates are sometimes incorrectly equated with the sustainable yield of an aquifer (Meinzer, 1923; Bredehoeft *et al.*, 1982; Bredehoeft, 2002; Alley and Leake, 2004). The term *sustainable yield* or *safe yield* refers to the rate at which water can be withdrawn from an aquifer without causing adverse impacts. Those impacts could be in the form of decreased discharge to streams and wetlands, land subsidence, or induced contamination of groundwater, for example, by seawater intrusion. The notion that recharge is equivalent to sustainable yield is based on an incomplete or incorrect conceptual model of a hydrologic system. Knowledge of recharge rates is important for determining sustainable yields in many groundwater systems (Sophocleous *et al.*, 2004; Devlin and Sophocleous, 2005), but recharge rates by themselves are not sufficient for determining sustainability (Bredehoeft *et al.*, 1982; Bredehoeft, 2002). The effects of changes in groundwater levels on groundwater discharge rates and aquifer storage must also be considered. From a hydrologic perspective, sustainable yield is best studied within the context of the entire hydrologic system of which the aquifer is a part, but decisions as to what constitutes a sustainable yield often involve more than just hydrologic considerations. Ecological, cultural, economic, and other considerations should help to determine the acceptability of any effects related to groundwater development (Alley and Leake, 2004).

1.4.1 Spatial and temporal variability in recharge

Recharge rates vary in space in both systematic and random fashions. This is true for both focused and diffuse recharge. Systematic trends often are associated with climatic trends, but land use and geology are also important. Statewide maps of estimated annual recharge for Texas (Figure 1.3; Keese *et al.*, 2005) and Minnesota (Lorenz and Delin, 2007) both

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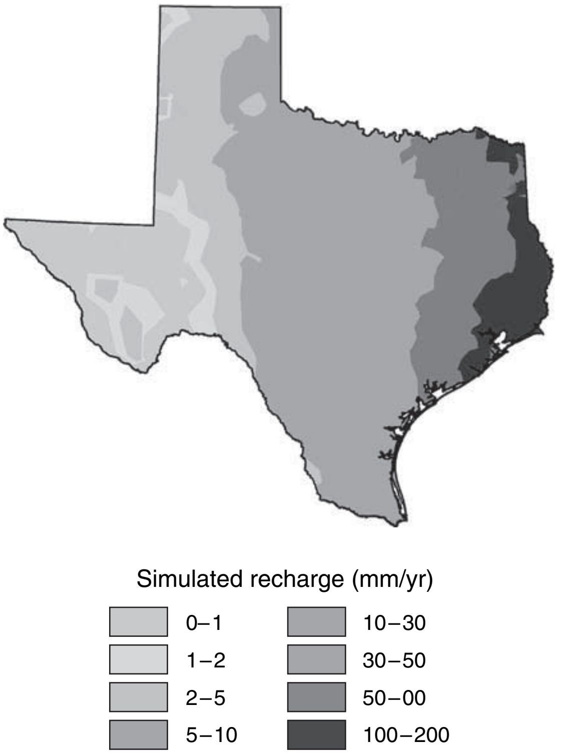

Figure 1.3 Map of average annual recharge rate for the state of Texas (Keese *et al.*, 2005).

display trends similar to those in statewide maps of annual precipitation. The concept of recharge rates increasing with increasing precipitation rates is certainly intuitive – recharge cannot occur if water is not available. The random factor in recharge variability can be viewed as local-scale variability that can be attributed, for example, to natural heterogeneity in permeability in surface soils or variability in vegetation. Any of the factors addressed below can contribute to apparent random variability. Delin *et al.* (2000) found that annual recharge varied by more than 50% within what appeared to be a uniform 2.7-hectare agricultural field simply because of slight differences in surface topography; the total relief in the field was less than 1.5 m. It could be argued that this difference in topography was not random; indeed, distinguishing between systematic and random patterns of recharge is sometimes a matter of scale. In the context of the entire upper Mississippi River valley, the topographic differences in this field are minute, apparently random; to someone standing in the field during a rain storm, the systematic pattern in recharge is obvious.

Recharge also varies temporally. Seasonal, multiyear, or even long-term trends in climate affect recharge patterns. Because of its close link to climate, temporal variability of recharge is addressed more thoroughly in Section 1.4.2. Changes in land use or in vegetation type and density can also result in large changes in recharge rates over time.

The importance of spatial and temporal variability of recharge must be considered within the context of study objectives. Spatial variability may not be critical for groundwater resource evaluation if an average rate of recharge can be determined for an entire aquifer. Spatial variability is important, though, for assessing aquifer vulnerability to contamination; therefore, methods that provide point estimates of recharge may be appropriate. Historically, many groundwater-flow models were developed under the assumption that recharge was constant in time. Current model applications typically allow recharge to vary over time but hold it constant for periods of months or years. Recent advances in incorporating landscape features into combined surface-water and groundwater flow (Section 3.6) will allow impacts of climate, land-use, and vegetation change on water resources to be examined at unprecedented levels of temporal and spatial variability.

1.4.2 Climate

Climate variability is often the most important factor affecting variability in recharge rates. Precipitation, the source of natural recharge, is the dominant component in the water budget for most watersheds. The relation between spatial trends of precipitation and recharge has been noted in Section 1.4.1. Temporal variability in precipitation also is important. Seasonal, year-to-year, and longer-term trends in precipitation, as well as frequency, duration, and intensity of individual precipitation events also affect recharge processes. Conditions are most favorable for water drainage through

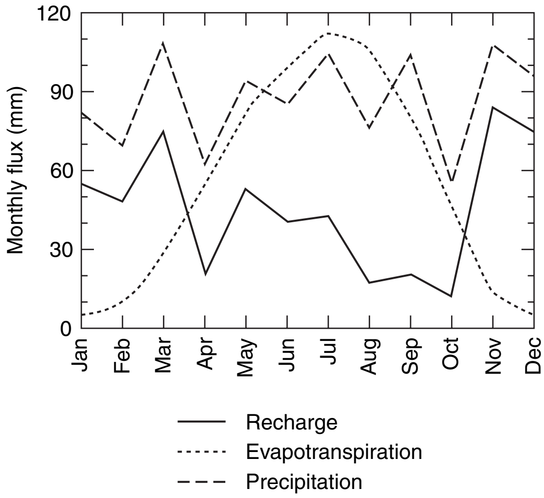

Figure 1.4 Average monthly recharge, evapotranspiration, and precipitation for the 2-year period beginning in April 1950 for the Beaverdam Creek watershed in eastern Maryland. Recharge occurs throughout the year, but most of it occurs in the months of November through March when evapotranspiration rates are low (after Rasmussen and Andreasen, 1959).

the unsaturated zone to the water table when precipitation rates exceed evapotranspiration rates. In regions outside of the tropics, evapotranspiration rates follow a seasonal trend, with highest rates occurring during summer months and lowest rates in winter months. If precipitation rates are fairly uniform throughout the year, the most likely time of the year for drainage to occur is winter through spring, when precipitation rates exceed evapotranspiration rates. At a site in the eastern United States, Rasmussen and Andreasen (1959) estimated that 62% of recharge over a 2-year period occurred in the months of November through March (Figure 1.4); precipitation was relatively uniform throughout the year, but evapotranspiration rates were lowest during these months.

Duration and intensity of individual precipitation events can have a large influence on recharge in some settings. On the humid, windward side of the Hawaiian Islands, precipitation and evapotranspiration rates are relatively uniform throughout the year. Recharge occurs at any time of the year in response to intense rain storms, when the total precipitation for a day exceeds the daily evapotranspiration rate (Ahuja and El-Swaify, 1979).

In arid regions, focused recharge from ephemeral streams and playas is often the dominant form of recharge. The frequency and duration of streamflow play important roles in the recharge process. The frequency of streamflow in Rillito Creek in Tucson, Arizona, coincides with the frequency of recharge events. Pool (2005) showed that interannual variability in recharge from the creek is linked to the El Niño/Southern Oscillation climate trend. Years dominated by El Niño conditions (high winter precipitation rates) produced significantly higher streamflow and recharge rates than years dominated by La Niña conditions.

1.4.3 Soils and geology

Permeabilities of surface and subsurface materials can greatly affect recharge processes. Recharge is more likely to occur in areas that have coarse-grained, high-permeability soils as opposed to areas of fine-grained, low-permeability soils. Coarse-grained soils have a relatively high permeability and are capable of transmitting water rapidly. The presence of these soils promotes recharge because water can quickly infiltrate and drain through the root zone before being extracted by plant roots. Finer-grained sediments are less permeable, but are capable of storing greater quantities of water. Thus, in areas of finer-grained sediments, one would expect decreased infiltration, enhanced surface runoff, increased plant extraction of water from the unsaturated zone, and decreased recharge relative to an area of coarser-grained sediments. Permeability also is important in terms of focused recharge. High-permeability streambeds facilitate the exchange of surface water and groundwater. In the Black Hills of South Dakota, most recharge to the Madison Limestone aquifer occurs at high elevations as focused flow from streams that cross rock outcrops (Swenson, 1968; Downey, 1984). In karst regions, dissolution cavities or sinkholes that have developed in the geologic material can rapidly channel streamflow directly to an

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aquifer; these cavities also facilitate groundwater discharge in the form of springs.

Subsurface geology influences discharge processes as well as recharge processes. If the rate of discharge from an aquifer is less than the recharge rate, water storage within the aquifer increases. Aquifer storage can reach a maximum at which point additional recharge cannot be accepted, regardless of the amount of precipitation. This condition typically leads to enhanced runoff.

Geophysical techniques have a wide range of uses in geologic and hydrologic studies, providing information on the electrical, physical, and chemical properties of surface and subsurface sediments. In regards to quantifying groundwater recharge, geophysical methods are most useful for determining soil-water content (Section 5.2.1) and changes in subsurface water storage (Section 2.3.3). However, information obtained from the application of geophysical techniques is also useful in a qualitative sense. Geophysical techniques can be used to infer aquifer geometry and hydraulic properties, important information for shaping conceptual models of hydrologic systems and for constructing computer models of groundwater flow (Robinson *et al.*, 2008a).

1.4.4 Surface topography

Land-surface topography plays an important role for both diffuse and focused recharge. Steep slopes tend to have low infiltration rates and high runoff rates. Flat land surfaces that have poor surface drainage are more conducive to diffuse recharge; these conditions also favor flooding. Small, often subtle depressions can have a profound influence on infiltration rates. Delin *et al.* (2000) showed that, even with highly permeable soils, slight depressions in an apparently uniform agricultural field caused runoff to be focused in certain areas, with the result that infiltration (and recharge) in those areas was substantially greater than that in the rest of the field. Even with uniform surface characteristics, apparent infiltration rates increase in the downslope direction along a long hill slope (Dunne *et al.*, 1991) because downslope portions of the hill are exposed to runoff from upslope portions as well as precipitation. Local relief, orientation, and altitude of mountain ranges are additional topographic factors that can affect recharge processes (Stonestrom and Harrill, 2007).

1.4.5 Hydrology

A conceptual model of recharge processes needs to consider the surface-water and groundwater flow systems and how they are linked. Are streams in the area perennial or ephemeral? Are streams gaining (receiving groundwater discharge) or losing (providing recharge)? A single stream could conceivably be losing water to an aquifer in one reach, but gaining water in another reach; the difference between groundwater and surface-water elevations, according to Darcy's law, determines whether water is moving to or from the subsurface. These are key questions, the answers to which will help shape the conceptual model.

The depth to the water table also is important. If the unsaturated zone is thin, infiltrating water can quickly travel to the water table; recharge may be largely episodic, occurring in response to any large precipitation event. However, shallow water tables are also susceptible to groundwater discharge by plant transpiration. Therefore, water that recharges shallow subsurface systems may only reside in the saturated zone for a short time before it is extracted by plant roots and returned to the atmosphere. Thick unsaturated zones are less likely to have episodic recharge events; recharge would be expected to be seasonal or quasi-steady because wetting fronts moving through the unsaturated zone tend to slow with depth and multiple fronts may coalesce and become indistinguishable from each other.

1.4.6 Vegetation and land use

Vegetation and land use can have profound effects on recharge processes. Types and densities of vegetation influence patterns of evapotranspiration. A vegetated land surface typically has a higher rate of evapotranspiration (and, hence, less water available for recharge) than an unvegetated land surface

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under similar conditions. The depth to which plant roots extend influences the efficiency with which plants can extract water from the subsurface. Trees, for example, are capable of drawing moisture from depths of several meters or more. In contrast, shallow-rooted crops cannot access soil water that penetrates to those depths. Thus, enhanced recharge rates in areas with shallow-rooted vegetation are seen in some semiarid regions when native perennial vegetation is replaced by shallow-rooted crops (Allison *et al*, 1990; Scanlon *et al.*, 2005; Leblanc *et al*, 2008). Nonirrigated agricultural crops can have higher or lower evapotranspiration rates than native plants; therefore, it is difficult to generalize as to whether the potential for recharge will increase or decrease due to changes in vegetation alone. In most settings, the influence of vegetation is seasonal; in periods of senescence, the presence of plants can actually promote recharge. Decay or shrinkage of roots can expose cavities that can act as preferential flow channels and enhance infiltration. Plowing and tilling in agricultural fields can have opposing effects – breaking up surface crusts, thus increasing the potential for infiltration – and destroying preferential flow channels, thus decreasing infiltration potential. Satellite remote sensing (Section 2.5) can provide information on surface characteristics, such as vegetation type and percent coverage, leaf area index, and land use that can be useful in formulating a conceptual model (Brunner *et al.*, 2007).

In the Murray Basin of Australia, native eucalyptus trees were gradually replaced with nonirrigated agricultural crops through the 1900s. Allison and Hughes (1983) estimated natural recharge rates under native vegetation to be less than 0.1 mm/yr. After clearing and subsequent cropping, estimated recharge rates increased by up to two orders of magnitude (Allison *et al.*, 1990). Unfortunately, the increased recharge has led to increased leaching of salts to groundwater and subsequently to the Murray River and its tributaries.

Conversion from natural savannah to nonirrigated millet crops over large areas of southwest Niger since the 1950s has produced soil crusting on slopes, resulting in increased runoff and focused recharge beneath ephemeral ponds that collect runoff (Leblanc *et al.*, 2008; Favreau *et al.*, 2009). Increased recharge rates arising from the land-use change can explain the paradoxical relationship between rising groundwater levels (about 4 m between 1963 and 2007) and decadal droughts (23% average annual decline in precipitation from 1970 to 1998 relative to the previous two decades). Areally averaged recharge rates are estimated to have increased from 2 to 25 mm/yr (Favreau *et al.*, 2009).

Irrigation can play an important role in groundwater recharge. *Irrigation return flow* is any excess irrigation water that drains down beneath the root zone or is captured in drainage ditches. It constitutes a significant amount of recharge in many areas, especially in arid or semiarid regions where natural recharge rates are low. Fisher and Healy (2008) studied recharge processes at two irrigated agricultural fields in semiarid settings; virtually all of the annual recharge occurred during the irrigation season and was attributed to irrigation return flow. Faunt (2009) used a complex groundwater-flow model to show that, in addition to the natural recharge that occurs during winter to aquifers in California's Central Valley, recharge also occurs during the growing season as a result of irrigation return flow. Within the United States, flood irrigation has gradually been replaced with more efficient sprinkle or drip irrigation systems; conversion to these new methods has reduced return flows substantially in some areas (McMahon *et al.*, 2003).

Urbanization brings about many land-surface changes that can have significant ramifications for recharge processes. Roads, parking lots, and buildings all provide impervious areas that can inhibit recharge. Runoff diversions are common features in urban landscapes. Diversions may lead to surface-water bodies or to infiltration galleries. In the former case, overall recharge for the area is reduced. In the latter case, recharge may not necessarily be reduced, but at the very least it is redirected and may change from a diffuse source to a focused